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Coal Burst Prevention Technology and Engineering Practice in Ordos Deep Mining Area of China

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Abstract: With the coal mines in western China entering the field of deep mining, the problem of coal burst is becoming more and more serious. According to the characteristics of deep mining, it is an urgent problem that requires the development of an efficient and reasonable coal burst prevention and control plan to guide project practices. This study takes the typical deep mining area in Ordos as the research background, according to the stress state of the coal mining area and the load form of induced coal burst, which, in Ordos deep mining, is divided into the typical and atypical type. The former is caused by the superposition of high in situ stress and strong mining-induced stress, while the latter is due to the combination of high in situ stress, strong mining-induced stress, and external stress disturbances. Combined with theoretical analysis, numerical simulation, and field measurement, it is shown that the stress level of the Ordos deep mining area is higher than that of the shallow original rock, and the difference of the three-dimensional stress between coal and rock mass is greater. The concentration degree and influence range of mining-induced stress obviously increase. Coal and rock mass are more prone to instability and failure due to external disturbances. Based on the stress control theory, the prevention and control strategies of coal burst in different types of deep mining are put forward. In addition, the prevention and control technology system of coal burst in the Ordos deep mining area is established. The field engineering practice has been carried out to realize the efficient prevention and control of coal burst.

Keywords: coal burst; Ordos deep mining; typical type; stress disturbance; atypical type

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1. Introduction

With the development of coal mining in China, more and more coal mines in western China have been subjected to coal burst, one of the most important disasters threatening safe production [1–4]. At present, the mining depth of coal mines in China has increased by 10~25 m every year. It can be predicted that the number of coal bursts in mines in China will continue to increase in the next 10 years [5,6]. The Ordos deep mining area is the largest coal production base in China, and coal bursts have occurred more than 10 times; how to effectively prevent and control coal bursts in this area will become the focus of scientific research on coal mine safety. Deep mining, compared to shallow mining, is characterized by high confining pressure, high temperature, and high pore pressure. A large number of studies show that when the coal seam reaches a certain depth, the mechanical properties of coal will change significantly [7]. It is mainly manifested in two aspects: firstly, the constitutive relationship changes from linear elasticity in the shallow part to visco-elastic nonlinearity in the deep part; and secondly, the stress release mode of coal and rock mass changes from shallow linear to deep non-linear. As a result, it is difficult to eliminate the high-level stress in the coal and rock mass by a one-time pressure relief in the deep mining process. In addition, it is necessary to release the visco-elastic deformation energy by multiple rounds of, or even continuous, pressure relief. Especially under the influence of dynamic load superposition caused by the structural instability of hard rock strata and fault activation, a coal burst is easily induced. Therefore, the prevention and control of coal bursts in the Ordos deep mining area is much more difficult, and it is urgent to put forward targeted prevention and control technology according to its characteristics.

In view of deep coal mining, scholars at home and abroad have carried out a lot of research on the mechanical characteristics of coal and rock mass, the in situ stress field, and the mining-induced stress field. Combined with nonlinear theory, fractal theory, black box theory, and damage mechanics theory, a variety of coal burst mechanism models have been proposed, and a method has been suggested to prevent and control coal burst by changing the mechanical properties of coal and rock mass, and reducing stress concentration [8–19]. With the increase of the number of coal burst mines in the Ordos deep mining area and the shift of research focus to prevention and control, how to formulate efficient and reasonable prevention and control schemes for coal burst based on the characteristics of deep mining and guiding field prevention and control has become an urgent problem to be solved. For a more scientific prevention and control of coal burst in the Ordos deep mining area, the concept of typical and atypical coal bursts is put forward. Based on the influencing factors of coal bursts in the Ordos deep mining area, the prevention and control strategies for different types of coal bursts in the Ordos deep mining area are proposed, and the field engineering practice is carried out. The research results are expected to provide theoretical and technical support for coal burst prevention and control in this area.

2. Classification of Coal Burst in Ordos Deep Mining Area

2.1. Analysis of Stress State in Coal Mining

The coal mining engineering area in plate tectonics and mine engineering geological conditions are controlled by tectonic movement. Tectonic stress is produced by plate collision and extrusion, which will be transmitted to the secondary plate and tectonic block through the coal and rock mass. Tectonic stress plays a controlling role in the stress environment of coal mining. The redistribution of stress in the coal and rock mass is caused by tectonic movement to achieve a new equilibrium. The results of stress distribution in the coal and rock mass can be divided into the following four cases:

(1) Region of stress reduction. The stress cannot reach the condition of coal and rock mass failure, resulting in the crust being in a stable state. When coal mining and other engineering activities are carried out, they will not cause dynamic phenomena that would affect human engineering activities, and it is safe.
(2) Region of simple increased stress. The stress increases, but does not reach the critical condition for the failure of coal and rock mass, so it is in a relatively stable state. If coal mining activities and other engineering activities are carried out, it is necessary to take certain prevention and treatment measures to ensure safety.
(3) Region of increased stress. The stress rises to a critical state, and if coal mining activities and other engineering activities are carried out, coal mine dynamic disasters such as coal burst may occur. It is necessary to take effective prevention and treatment measures to ensure safety.
(4) Region of stress release. The stress level exceeds the failure limit of the coal and rock mass, which is not directly related to human engineering activities. There will be strong tectonic activity such as earthquakes, tsunamis, and volcanic eruptions, and stress will be released to achieve equilibrium.

When coal mines enter deep conditions, the stress state of the coal and rock mass is usually in state (2) and state (3). Therefore, according to the stress state of the coal and rock mass in the Ordos deep mining area, coal burst can be divided into two types, that is, typical coal burst and atypical coal burst.

2.2. Typical Coal Burst in Ordos Deep Mining Area

Typical coal burst in the Ordos deep mining area refers to the stress state of coal and rock mass being in state (3). That is, the stress in the coal and rock mass has reached the critical instability state. When the coal and rock mass are affected by mining engineering, the critical condition of coal burst can be exceeded. Typical coal burst in the Ordos deep mining area occurrence conditions can be expressed as follows:

$$\sigma_1 + \sigma_2 \geq \sigma_0 \tag{1}$$

where σ_1 is the original rock stress, σ_2 is the mining-induced stress, and σ_0 is the critical strength of coal and rock mass.

According to the above definition and analysis, there are two main sources of stress in typical coal burst mines, that is, high in situ stress and high concentrated mining-induced stress. The occurrence mechanism of typical coal burst in the Ordos deep mining area can be represented by Figure 1. Considering the characteristics of typical coal burst, the key point of the prevention and control is pressure relief, and its purpose is to slow down the rate of stress release.

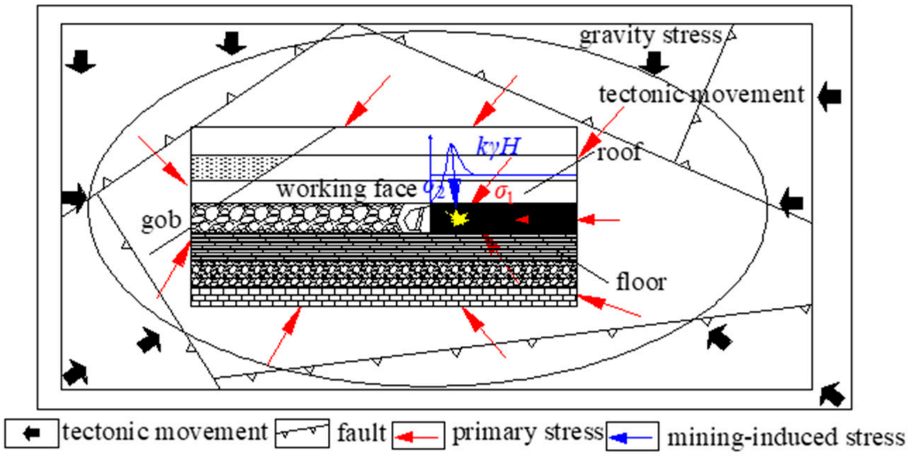


Figure 1. Schematic diagram of the mechanism of typical coal burst in the Ordos deep mining area.

2.3. Atypical Coal Burst in Ordos Deep Mining Area

Atypical coal burst in the Ordos deep mining area refers to the stress state of coal and rock mass being in state (2). That is, under mining disturbance, the stress of the coal and rock mass does not reach the critical state. When the coal and rock masses are subjected to external disturbances, such as roof weighting, structural instability of hard rock strata and fault slip, the stress in the coal and rock masses exceeds the critical condition. Atypical coal burst in the Ordos deep mining area occurrence conditions can be expressed as follows:

$$\sigma_1 + \sigma_2 + \sigma_3 \geq \sigma_0 \tag{2}$$

where σ_1 is the original rock stress, σ_2 is the mining-induced stress, σ_3 is the external disturbance stress, and σ_0 is the critical strength of coal and rock system.

According to the above definition and analysis, there are three main sources of stress in typical coal burst mines, that is, high in situ stress, high concentrated mining-induced stress and external disturbance stress. The occurrence mechanism of atypical coal burst in the Ordos deep mining area can be represented by Figure 2.

According to the characteristics of typical coal burst, the key point of the prevention and control is pressure relief, and its purpose is to slow down the rate of stress release, reduce external disturbances and weaken stress transmission capacity.

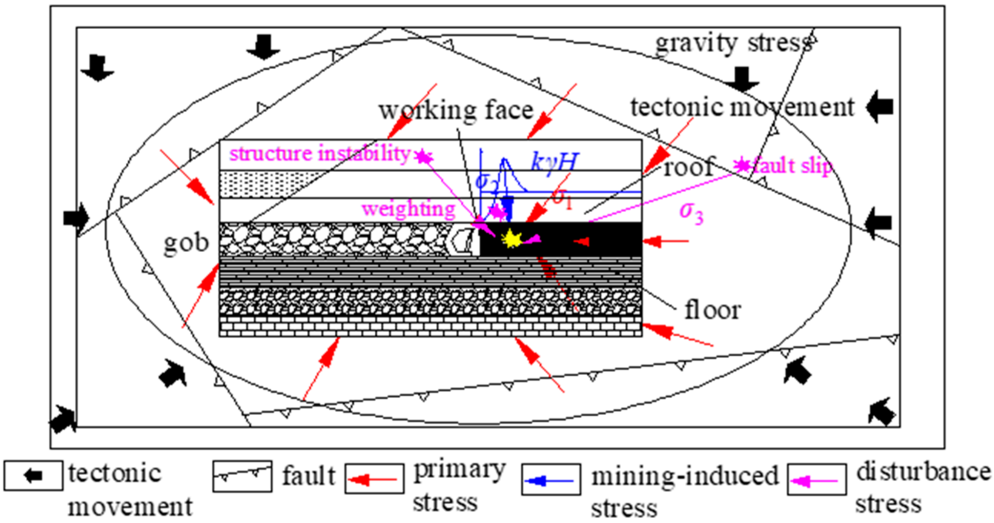


Figure 2. Schematic diagram of the mechanism of atypical coal burst in the Ordos deep mining area.

3. Analysis of Influencing Factors of Coal Burst in Ordos Deep Mining Area

3.1. Regional Geological Structure of Ordos Basin

Ordos Basin is located at the junction of the eastern and western tectonic domains in China. It is a superimposed basin controlled by multistage tectonic and sedimentary evolution cycles. The internal structure of the basin is simple, the stratum is gentle, and the activity is weak, which is mainly manifested in the structural forms of uplift, depression, wide and gentle fold, etc. According to the current structural development morphology and space-time distribution characteristics of the Ordos Basin, the basin includes a secondary structural unit in the Weihe Graben and six tertiary structural units in the western margin thrust zone, the eastern margin western Shanxi flexure zone, Yimeng uplift, Tianhuan depression, northern Shaanxi monocline, Weibei uplift and Weihe Graben.

3.2. Primary Stress Characteristics of Ordos Deep Mining Area

In order to analyze the difference of primary stress characteristics between deep mining and shallow mining in Ordos, the in situ stress data of 9 shallow mines in Ordos are obtained through field measurement and investigation [20]. The results are shown in Table 1. The depth of the 9 groups of data is between 76 m~375 m. The above 9 coal mines all belong to the same in situ stress field ($\sigma_H > \sigma_v > \sigma_h$), which is a typical stress field dominated by tectonic stress. In the same way, the in situ stress data of 11 deep mines in Ordos are obtained through field measurement and investigation [20]. The results are shown in Table 2.

Table 1. Measured data of in situ stress in the Ordos shallow mining area.

No	Name of Mine	Depth (m)	σ_H (MPa)	σ_h (MPa)	σ_v (MPa)
1	Buertai Coal Mine	375	9.34	8.72	9.94
2	Baode	347	9.84	8.19	9.20
3	Bulianta Coal Mine	230	6.57	5.15	5.76
4	Suancigou Coal Mine	303	7.72	4.06	7.60
5	Baoshan Coal Mine	112	4.06	2.08	2.81
6	Dadi Coal Mine	76	4.26	2.48	1.90
7	Talahao Coal Mine	167	6.69	2.52	3.48
8	Bojianghaizi Coal Mine	370	16.60	9.80	10.00
9	Huoluowan Coal Mine	165	4.62	2.20	3.60

Table 2. Measured data of in situ stress in the Ordos deep mining area.

No	Name of Mine	Depth (m)	σ_H (MPa)	σ_h (MPa)	σ_v (MPa)
1	Hongqinghe Coal Mine	719	27.87	16.61	16.39
2	Menkeqing Coal Mine	720	24.56	15.76	18.20
3	Shilawusu Coal Mine	660	27.16	10.91	16.24
4	Hulusu Coal Mine	650	25.74	9.39	15.49
5	Bayangaole Coal Mine	635	27.86	15.87	17.38
6	Muduchaideng Coal Mine	660	15.71	7.73	13.92
7	Nalinhe No.2 Coal Mine	550	19.22	14.30	13.75
8	Yingpanhao Coal Mine	720	25.50	20.30	18.36
9	Tarangaole Coal Mine	600	17.15	6.40	14.35
10	Hongqingliang Coal Mine	500	20.30	11.57	12.05
11	Changcheng No.2 Coal Mine	738	24.50	10.24	15.50

The depth of the 11 groups' data is between 500 m~738 m. The above 11 coal mines all belong to the same in situ stress field ($\sigma_H > \sigma_v > \sigma_h$), which is a typical stress field dominated by tectonic stress. The ratio of stress is an important index for analyzing the stress characteristics of in situ stress.

$$\begin{aligned} k_1 &= \sigma_H / \sigma_v \\ k_2 &= \sigma_h / \sigma_v \\ k_3 &= \sigma_H / \sigma_h \end{aligned} \tag{3}$$

where σ_H is maximum horizontal stress, σ_h is minimum horizontal stress, and σ_v is vertical.

The calculation results are shown in Table 3.

Table 3. Statistical table of in situ stress characteristic values in the Ordos deep mining area.

No	Name of Mine	Depth (m)	k_1	k_2	k_3
1	Hongqinghe Coal Mine	719	1.70	1.01	1.68
2	Menkeqing Coal Mine	720	1.35	0.32	1.56
3	Shilawusu Coal Mine	660	1.67	0.67	2.49
4	Hulusu Coal Mine	650	1.66	0.61	2.74
5	Bayangaole Coal Mine	635	1.60	0.91	1.76
6	Muduchaideng Coal Mine	660	1.13	0.56	2.03
7	Nalinhe No.2 Coal Mine	550	1.40	1.04	1.34
8	Yingpanhao Coal Mine	720	1.39	1.11	1.26
9	Tarangaole Coal Mine	600	1.20	0.45	2.68
10	Hongqingliang Coal Mine	500	1.68	0.96	1.75
11	Changcheng No.2 Coal Mine	738	1.58	0.66	2.39

It indicates that the minimum value of k_1 is 1.13, and the maximum value is 1.70. There are 5 coal mines with $1 \leq k_1 < 1.5$, and 6 coal mines with $1.5 \leq k_1 < 2$. By comparison and analysis of the measured data, k_1 is between 0.94 and 2.24. The value of k_1 in the shallow coal mine is smaller than that measured in the deep coal mine. Therefore, with the increase of the depth, the k_1 approximately shows an increasing trend. It indicates that the maximum horizontal stress in deep coal mine is stronger than that in shallow coal mine.

The minimum value of k_2 is 0.32, and the maximum value is 1.11. There are 2 coal mines with $k_2 < 0.5$, 6 coal mines with $0.5 \leq k_2 < 1$, and 3 coal mines with $1 \leq k_2 < 1.5$. Through comprehensive analysis and comparison, the k_2 in the shallow area is between 0.53 and 1.31, which is obviously lower than that in the deep area. Therefore, with the increase of the depth, the k_2 approximately shows an decreasing trend. It points out that the difference between the minimum horizontal stress and vertical stress in the deep coal mine is obviously larger than that in the shallow coal mine.

In the measured data of 11 mines, the minimum value of k_3 is 1.26, and the maximum value is 2.74. There are 2 coal mines with $k_3 < 1.5$, 4 coal mines with $1.5 \leq k_3 < 2$, 3 coal mines with $2 \le k_3 < 2.5$ and 2 coal mines with $k_3 \ge 2.5$. Based on the measured data, the measured value of k_3 in the shallow area is between 1.07 and 2.65, which is obviously lower than that in deep area. Therefore, with the depth rises, the value of k_3 obviously shows an increasing trend. To sum up, with mining depth increasing, the difference of coal and rock mass triaxial stress state becomes larger and larger. According to the Moore–Coulomb criterion [15], the larger the difference of the triaxial stress state, the more likely failure and instability will occur.

Therefore, when a coal mine in Ordos enters deep mining, the level of primary stress is higher than that in a shallow area, and the anisotropy is more obvious. As a result, the stress level of coal and rock mass accumulation is higher, and instability failure is more likely to occur. It provides foundation stress conditions for the occurrence of coal burst.

3.3. Mining-Induced Stress Characteristics of Ordos Deep Mining Area

In order to analyze the characteristics of mining-induced stress, a FLAC3D numerical model is established [21]. The characteristics of mining-induced stress of the same model with different depths are analyzed. According to the average of bulk density with 25 kN/m^3, the vertical stress at different depths is calculated. Specific values of the triaxial stress are shown in Table 4.

Table 4. Numerical simulation of in situ stress parameters in mines with different depths.

No	Depth (m)	σ_H (MPa)	σ_h (MPa)	σ_v (MPa)
1	400	15.00	7.50	10.00
2	600	22.50	11.25	15.00
3	800	30.00	15.00	20.00
4	1000	37.50	18.75	25.00

A total of 240,000 units and 251,991 nodes has been established, and the size of numerical model is length of 300 m, width of 400 m and height of 50 m. The top of the model is free boundary, and the others are fixed boundary. The primary stress field is applied according to the data in Table 2, and equivalent load is applied to simulate the upper part of the model. The numerical model is shown in Figure 3.

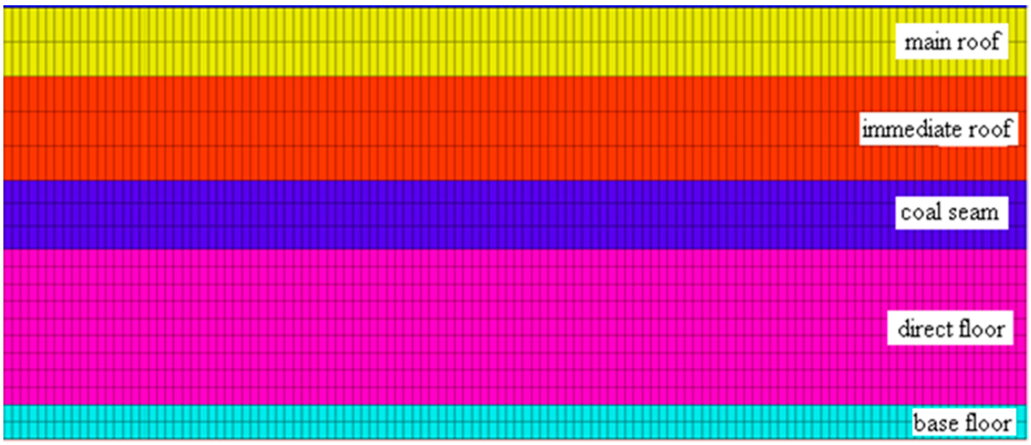


Figure 3. Numerical model of mining at different depths.

However, in the model, the length of the working face is 200 m and the thickness of the coal seam is 5 m. After the panel is mined 200 m, the vertical stress data within 100 m advance of the panel is extracted (shown in Figure 4).

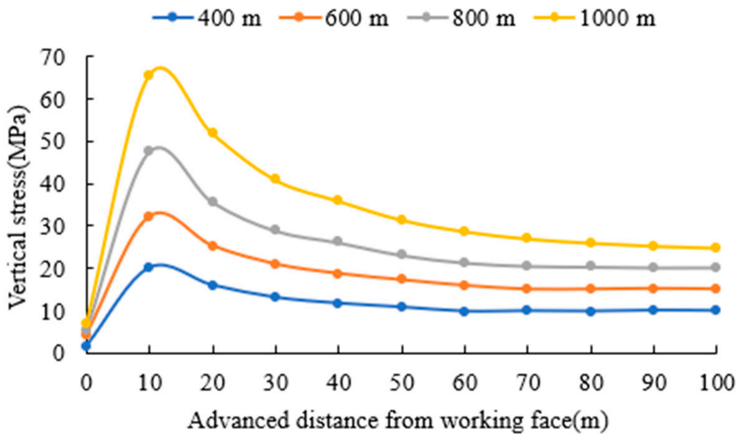


Figure 4. Advance stress distribution curves of mining at different depths.

As can be seen from the change in Figure 4, the influence range of concentrated stress is about 60 m for mining at depth of 400 m, 70 m for 600 m depth, 70 m for 800 m depth and 90 m for 1000 m depth. The influence range of concentrated stress shows an upward trend with the increase of mining depth. At 400 m depth, the concentrated stress peak is about 20.01 MPa, and the stress concentration coefficient is 2.01. At 600 m depth, the peak is about 32.11 MPa, and the coefficient is 2.14. At 800 m depth, the peak is about 47.42 MPa, and the coefficient is 2.37. At 1000 m depth, the peak is about 65.53 MPa, and the coefficient is 2.62. The degree of stress concentration increases with mining depth increasing. Therefore, when coal mines enter deep area, the disturbance of mining-induced stress is higher than that in shallow area. Both the degree and influence range of concentrated stress increase obviously, which provides the conditions of strong mining-induced stress for the occurrence of coal bursts.

3.4. External Disturbance Stress Characteristics of Ordos Deep Mining Area

External disturbances mainly include periodic weighting, overburden structure instability, and fault slip. Compared with shallow mining, deep mining has a higher level of basic stress and mining-induced stress. The external disturbance is more intense in deep mining, which is more likely to induce mine dynamic disasters such as coal burst. Taking the fault as an example, the numerical simulation method is adopted to analyze the external disturbance stress in deep mining. A total of 452,560 units and 462,429 nodes are established, and the size of the numerical model is length × width × height of 950 m × 400 m × 1000 m. Two faults are included in this numerical model, named as F25 and F18 (shown in Figure 5)

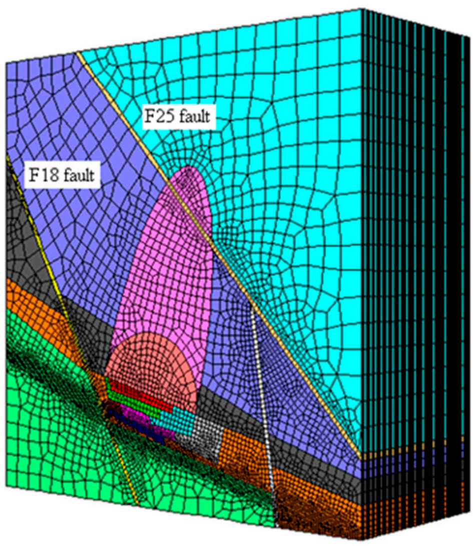


Figure 5. Numerical model including faults at different mining depths.

In this model, the primary stress at different mining depths is still assigned according to Table 4, and the length of the simulated working face is set as 160 m. When the panel is mined 200 m, the vertical stress at the point 10 m ahead of working face is extracted and the curve is drawn, as shown in Figure 6. At 400 m depth, the stress peak of F25 fault is 16.82 MPa with concentration coefficient of 1.68 and the influence range is about 50 m, the peak of F18 fault is 21.12 MPa with coefficient of 2.12 and the range is about 60 m. At 600 m depth, the peak of F25 fault is 28.81 MPa with coefficient of 1.92 and the range is about 70 m, the peak of F18 fault is 31.90 MPa with coefficient of 2.13 and the range is about 90 m. At 800 m depth, the peak of F25 fault is 41.78 MPa with coefficient of 2.09 and the range is about 70 m, the peak of F18 fault is 42.42 MPa with coefficient of 2.12 and the range is about 90 m. At 1000 m depth, the peak of F25 fault is 54.54 MPa with coefficient of 2.18 and the range is about 80 m, the peak of F18 fault is 56.37 MPa with coefficient of 2.25 and the range is about 100 m. With the increase of mining depth, the degree of fault stress concentration and the influence area exhibit an obvious increasing trend. Therefore, the deep mining fault is more likely to produce slip vibration, and the influence range of stress concentration is larger, and the disturbance to mining engineering is more intense.

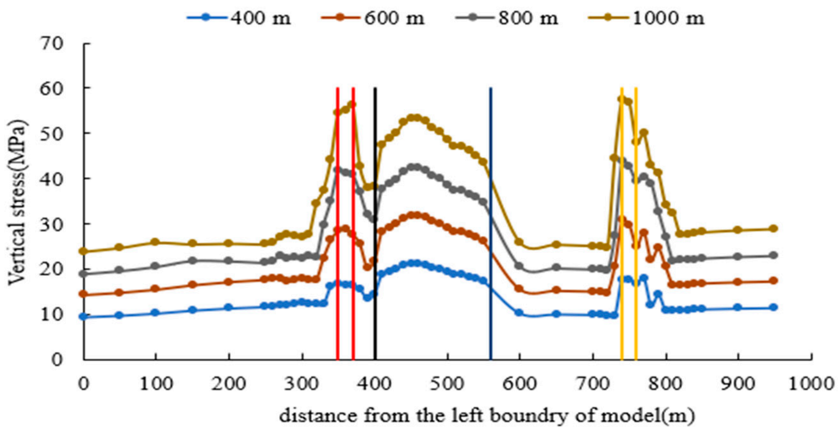


Figure 6. Vertical stress distribution curves of faults at different mining depths.

According to the above analysis, the reasons why coal mines in the Ordos deep mining area are more prone to coal bursts can be summarized as follows: (1) The level of primary stress in the Ordos deep mining area is higher than that in the shallow area, and the difference of the triaxial stress of the coal and rock mass is larger. The stress level accumulated in the coal and rock mass is higher. All these factors have promoted the occurrence of instability disasters in the coal and rock mass. (2) The influence of mining-induced stress is stronger in the Ordos deep mining area. The degree and influence range of concentrated stress obviously increase, which aggravate the accumulation of stress in the coal and rock mass. (3) Deep mining in Ordos is more prone to instability caused by external disturbance, and the influence scope and degree of faults and other structures are larger. It is more likely to lead to the instability of coal and rock mass.

4. Practice of Coal Burst Prevention and Control in Ordos Deep Mining Area

4.1. Prevention and Control Strategy of Rock Burst in Ordos Deep Mining Area

According to the two types of coal burst in the Ordos deep mining area, two corresponding strategies of prevention and control are proposed. Referring to the above research, the necessary conditions for the occurrence of typical coal bursts are high in situ stress and high concentrated mining-induced stress. Additionally, the necessary conditions for the occurrence of atypical coal bursts are high in situ stress, high concentrated mining-induced stress and external disturbance stress. Therefore, coal burst prevention and control strategies of the Ordos deep mining area are suggested as follows: Considering the typical coal burst in the Ordos deep mining area, coal burst prevention and control should avoid stress accumulation in coal and rock mass, and be appropriate to the coal mass pressure relief to improve the overlying structure. The main point is to unload the pressure of coal and improve its mechanical properties. The typical strategy is a large range of coal pressure relief, proper treatment of roof and floor, and strong support. Especially, when the depth is over 800 m, portal supporting and "O" type sheds should be used. Correspondingly, for atypical coal burst prevention and control, partial coal pressure relief, large scale of roof treatment and strengthening support are critical means. This contributes to stress release caused by period weighting or overlying structure instability. Additionally, a broken zone is formed in the roof and coal seam to increase the attenuation of external disturbance stress.

4.2. Stress Control Technology System of Coal Burst in Ordos Deep Mining Area

Based on the stress control theory in coal mines [22], the prevention and control of coal bursts in the Ordos deep mining area can be divided into three stages: roadway excavation stage, panel preparation stage, and panel mining stage. According to the key points of coal burst prevention and control in each stage, and the actual production conditions, the corresponding stress control technologies are put forward. (1) Stress control technology in roadway excavation stage: due to the particularity of coal and rock properties, and the stress environment in the Ordos deep mining area, the roadway surrounding rock can show obvious flow deformation during roadway excavation. It is suggested to use large-diameter borehole pressure relief or unloading blasting technology to relieve the pressure of coal seams. When the coal strength is high, unloading blasting technology is preferred. (2) Stress control technology in panel preparation stage: this stage is implemented after the end of roadway excavation, before the panel mining. Due to the disturbance of the roadway to the coal and rock mass in the range of stope, especially in the roadway, which is closed by mining gob, it is easy to produce a highly concentrated stress area. Thus, in this period, according to the type of coal burst in the Ordos deep mining area, it is recommended to carry out pressure relief and pre-cracking measures for coal seam and roof, respectively. In addition, large-diameter borehole pressure relief and unloading blasting technology can be used to relieve pressure in the high-concentrated stress area on both ribs. Both of these ways are good to reduce the disturbance of coal mining. Additionally, it is proposed to use hydraulic fracturing, deep hole blasting and ground hydraulic fracturing to treat the overlying strata. (3) Stress control technology in panel mining stage: when the panel is mined, the effect from mining is more intense than that of roadway excavation, and the external disturbance such as roof weighting and overlying structure instability is brought. It is necessary to carry out the second round of pressure relief. The support system shall be strengthened in high-risk areas such as advanced support to further improve the safety of coal burst. It is a good proposal that large-diameter borehole pressure relief and unloading blasting technology need to be adopted to achieve the second round of pressure relief in the area of high concentrated stress. Additionally, "O" type shed, "U" type shed and strong hydraulic support should be adopted to strengthen the roadway stability.

4.3. Prevention and Control Practice of Typical Coal Burst in Ordos Deep Mining Area

Hongqingliang Coal Mine is located in the north of Yimeng uplift. The layout plan of Hongqingliang Coal Mine is shown in Figure 7. The depth of mines No.3-1 coal seam in this area is 458~538 m. The thickness of that is 2.86–6.85 m, with an average of 4.87 m. The structure of that is simple, most of which contain one layer of gangue, and some including two layers of 0.15~0.62 m gangue. The inclination angle of the coal seam is 0~6°, with an average of 3°. The lithology of the roof is mainly sandy mudstone and siltstone, and some are fine grained sandstone, conglomerate or coarse-grained sandstone. The lithology of the floor is mainly sandy mudstone and mudstone. The overlying strata of Hongqingliang Coal Mine belong to weakly consolidated strata and contain a lot of clay minerals. The strength of coal seams is high and can reach 14 MPa locally. The width of coal pillars between 2 panels is 20~25 m.

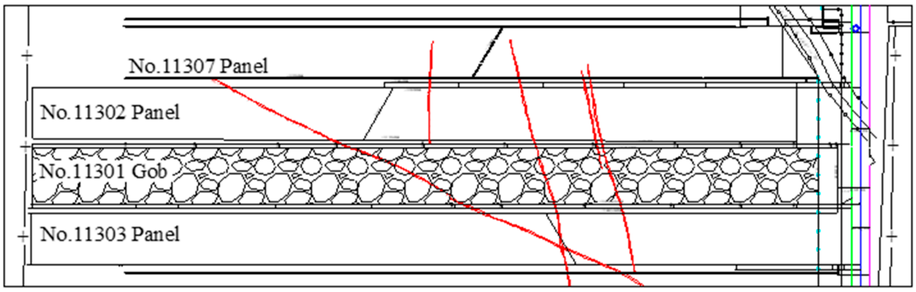
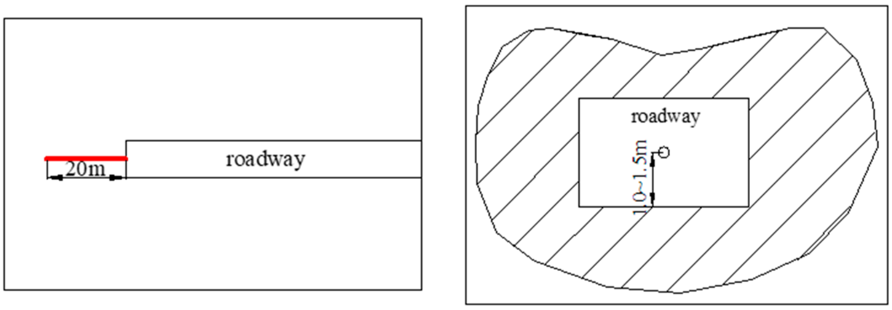


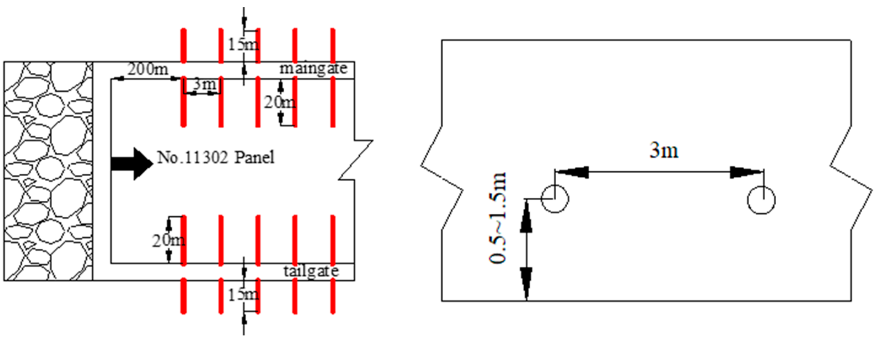
Figure 7. Hongqingliang coal mine excavation project plan.

Under the superposition of primary stress and mining-induced stress, the panel is easy to destabilize and lead to coal burst. Therefore, it belongs to typical coal burst. Therefore, Hongqingliang Coal Mine has formulated the three-in-one prevention and control measures of borehole pressure relief, high-strength bolt support, and advanced hydraulic support. The specific parameters of the measurements are as follows. (1) Roadway excavation stage: No.11302 Panel mainly adopts advanced borehole pressure relief technology. The diameter of pressure relief bore hole is 110 mm, the borehole depth is 20 m. The boreholes are arranged in a single row, with 1.0~1.5 m away from the floor. The plan and section of the pressure relief borehole are shown in Figure 8. (2) Panel preparation stage: No.11302 Panel mainly adopts strong bolt (cable) to further strengthen roadway support and control roadway deformation. (3) Panel mining stage: No.11302 Panel mainly adopts large diameter borehole pressure relief and advanced unit hydraulic support technology. The diameter of the pressure relief borehole is 110 mm, and the spacing is 3 m. The borehole depth in the coal pillar rib is 15 m. Another rib is 20 m, and the height from the floor plate is 1.5 m. The support distance of unit hydraulic support is 100~120 m. The plan and section of the pressure relief borehole are shown in Figure 9.



(**a**) (**b**)

Figure 8. Plan and section of the pressure relief borehole in roadway excavation stage of No.11302 Panel. (**a**) Plan. (**b**) Section.



(**a**) (**b**)

Figure 9. Plan and section of the pressure relief borehole in panel mining stage of No.11302 Panel. (**a**) Plan. (**b**) Section.

The maximum mining speed of No.11302 Panel is 12 m/day. Six months after the implementation of prevention and control measures, the microseismic monitoring event plan of No.11302 Panel is shown in Figure 10. In the microseismic system, green points means microseismic event energy $\leq 10^3$ J, yellow points means microseismic event energy $\leq 10^4$ J, and red points means microseismic event energy > 10^5 J. The microseismic monitoring results show that after a series of prevention and control measures in this mining area, the overall pressure of No.11302 Panel in Hongqingliang Coal mine is stable, and the energy level of microseismic events is mainly between 10^3~10^4 J, and no high energy event above 10^5 J appears.

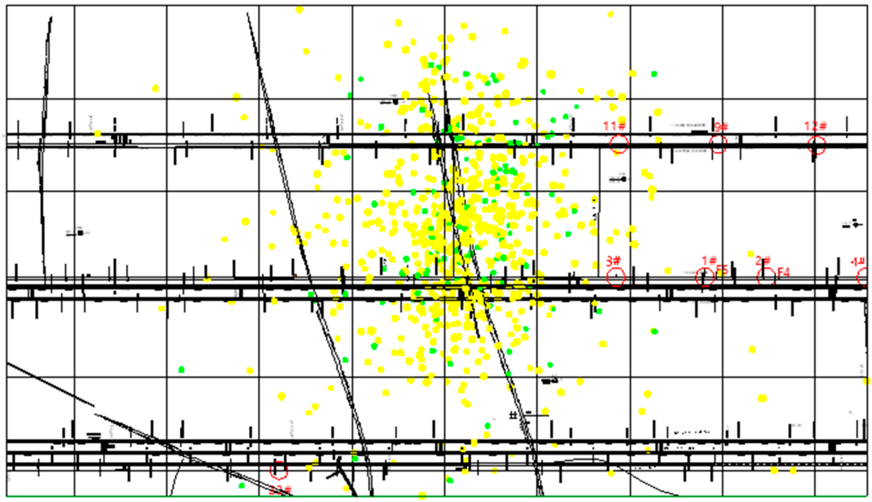


Figure 10. Microseismic event distribution of No.11302 Panel.

4.4. Prevention and Control Practice of Atypical Coal Burst in Ordos Deep Mining Area

Shilawusu Coal Mine is located in the south of the junction of Yimeng uplift and northern Shaanxi slope. Shilawusu Coal Mine mines exploits No.2-2 coal seam, with an average depth of 690 m. The immediate roof of #No.2-2 coal seam is sandstone or siltstone strata with a thickness that exceeds 10 m, and its uniaxial compressive strength is greater than 60 MPa. The width of coal pillars between 2 panels is 5~6 m. The layout plan of Shilawusu Coal Mine is shown in Figure 11.

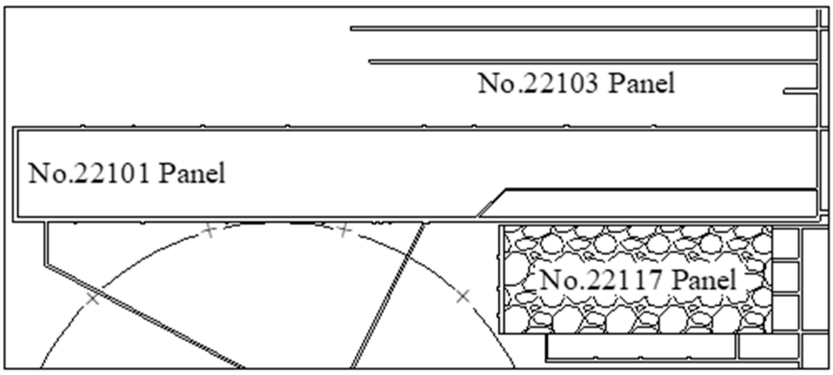


Figure 11. Shilawusu coal mine excavation project plan.

Shilawusu Coal Mine has high stress characteristics under the influence of North Shaanxi Slope. A coal burst is easily induced by the disturbance of hard rock strata instability. It belongs to atypical coal burst. Therefore, Shilawusu Coal mine has formulated the three-in-one prevention and control measures of roof hydraulic fracturing, borehole pressure relief and advanced hydraulic support. The specific parameters of the measures are as follows:

(1) Roadway excavation stage: No.22101 Panel mainly adopts advanced borehole pressure relief technology. The diameter of pressure relief bore hole is 150 mm with the spacing of 2 m. The borehole depth is 20 m, which is arranged in a single row, and the borehole is 1.0~1.5 m away from the floor. The plan and section of the pressure relief borehole are shown in Figure 12.

(2) Panel preparation stage: No.22101 Panel mainly adopts a single rib of large diameter borehole pressure relief and roof hydraulic fracturing technology. The diameter of the pressure relief borehole is 150 mm, and the spacing is 1 m. The borehole depth is 20 m, and the height from the floor plate is 1.2~1.5 m. The diameter of the hydraulic fracturing borehole is 42 mm. The fracturing position is the immediate roof with a thickness of 9.31 m, and the lithology is fine-grained sandstone. Additionally, another fracturing position is 19.84 m away from the No.2-2 coal seam, and the lithology is medium-grained sandstone with a thickness of 10.44 m. The plan and section of the pressure relief borehole and the hydraulic fracturing borehole are shown in Figures 13 and 14.

(3) Panel mining stage: No.22101 Panel mainly adopts large diameter borehole pressure relief and advanced unit hydraulic support technology. The diameter of the pressure relief borehole is 150 mm and the spacing is 1 m. The borehole depth is 20 m, and the height from the floor plate is 1.5 m. The support distance of the unit hydraulic support is 120~150 m. The plan and section of the pressure relief borehole are shown in Figure 15.

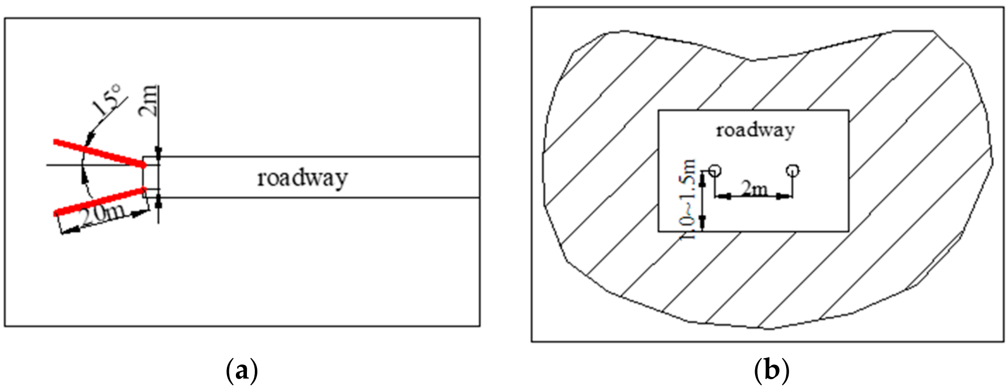


Figure 12. Plan and section of the pressure relief borehole in roadway excavation stage of No.22101 Panel. (**a**) Plan. (**b**) Section.

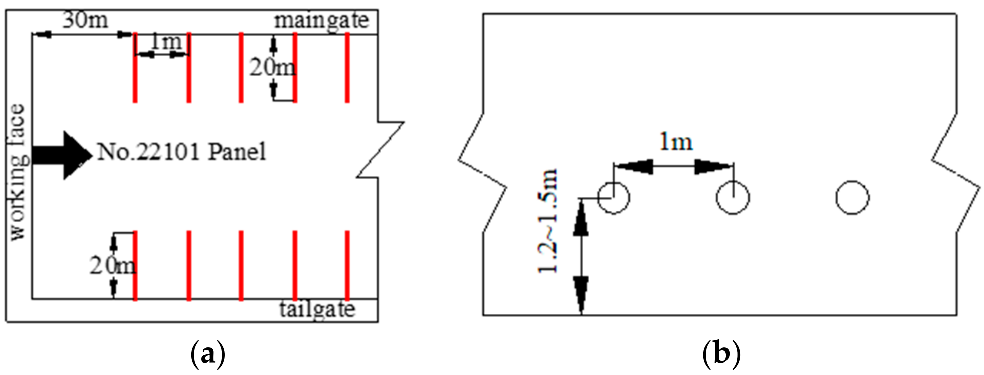
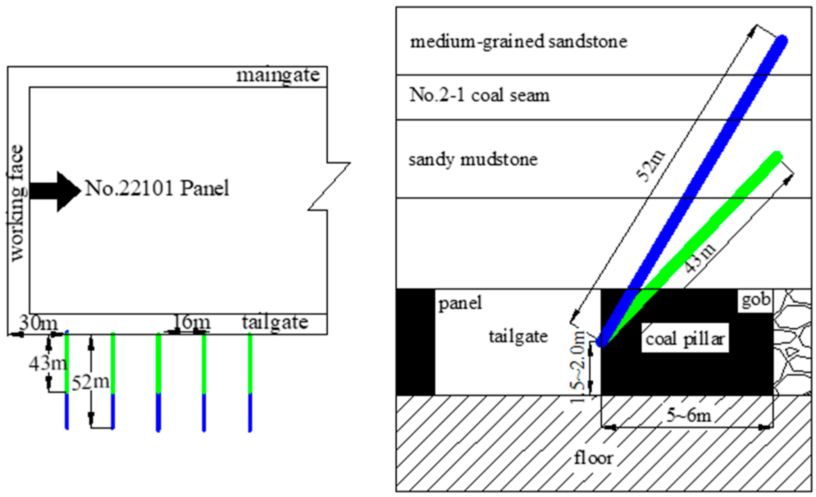


Figure 13. Plan and section of the pressure relief borehole in panel preparation stage of No.22101 Panel. (**a**) Plan. (**b**) Section.



(**a**) (**b**)

Figure 14. Plan and section of the hydraulic fracturing borehole in panel preparation stage of No.22101 Panel. (**a**) Plan. (**b**) Section.

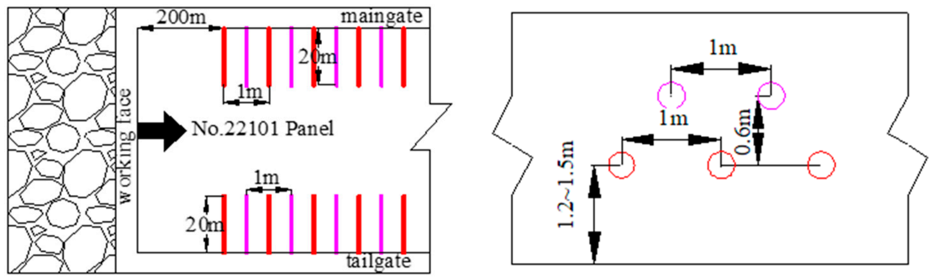


Figure 15. Plan and section of the pressure relief borehole in panel mining stage of No.22101 Panel.

The maximum mining speed of No.22101 Panel is 8 m/day. Through the implementation of roof hydraulic fracturing, the first weighting step distance of No.22101 Panel is 21.7 m, and the average periodic weighting step distance is 12.7 m. However, the first weighting step distance of the panel without hydraulic fracturing is about 60.5 m, and the periodic weighting step distance is 25~30 m. Obviously, the roof hydraulic fracturing technology effectively reduces disturbance of roof weighting to the panel. The microseismic monitoring data during the first weighting of No.22101 Panel are shown in Figure 16.

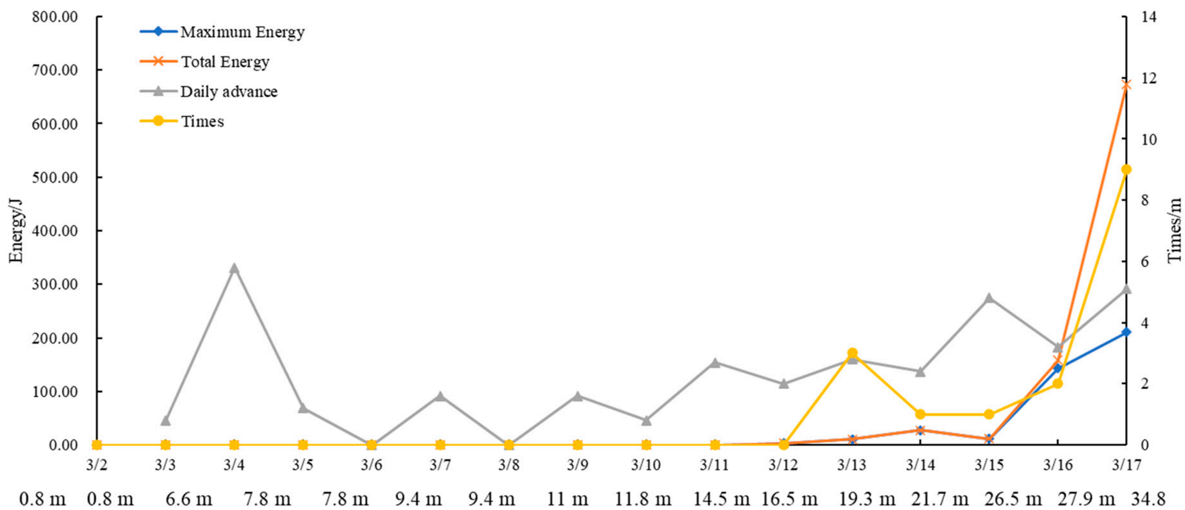


Figure 16. Microseismic data during the first roof weighting.

5. Conclusions

The prevention and control of coal burst in the Ordos deep mining area are systematically studied by using theoretical analysis, numerical simulation and field measurement methods. The following five conclusions are drawn:

(1) According to the stress state and load form of coal and rock mass in the Ordos deep mining area, the coal burst is divided into two types, that is, typical coal burst and atypical coal burst.
(2) The necessary conditions for the occurrence of typical coal burst are high in situ stress and high concentrated mining-induced stress. Additionally, the necessary conditions for the occurrence of atypical coal burst are high in situ stress, high concentrated mining-induced stress and external disturbance stress.
(3) The level of primary stress in the Ordos deep mining area is higher than that in shallow areas. The influence of mining-induced stress is stronger in the Ordos deep mining area. Deep mining in Ordos is more prone to instability caused by external disturbance. The above three conditions are the fundamental reasons for the easy occurrence of coal bursts in the Ordos deep mining area.
(4) Based on the control theory of coal burst, the prevention and control of coal bursts in the Ordos deep mining area can be divided into three stages: roadway excavation stage, panel preparation stage and panel mining stage. The corresponding stress control technology has been formed, and the dynamic prevention and control technology system of coal bursts in the Ordos deep mining area has been formulated.
(5) The effective strategy of typical coal burst prevention and control is a large range of coal pressure relief, proper treatment of roof and floor, and strong support. Especially, when the depth is over 800 m, portal supporting and "O" type sheds should be used. Additionally, the practical strategy of atypical coal burst prevention and control is partial coal pressure relief, large range of roof treatment, and strengthen support.

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Data Availability Statement: All data used in the article and relevant conclusions obtained therefrom are included in this article.

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